

# $B_s$ mixing



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# Outline

## Introduction: B mixing

## Theoretical framework

- Heavy Quark Expansion
- State of the art
- Non-perturbative parameters

## Lifetimes - Test HQE

- $\tau_{B^+} / \tau_{B_d}$
- $\tau_{B_s} / \tau_{B_d}$
- $\tau_{\Lambda_b} / \tau_{B_d}$
- $\tau_{B_c}$

## $B_q - \bar{B}_q$ -Oscillations

- $\Delta M$
- $\Delta\Gamma$  and  $\Delta\Gamma / \Delta M$
- $a_{fs}$  or  $\phi$
- New physics in mixing

## Outlook

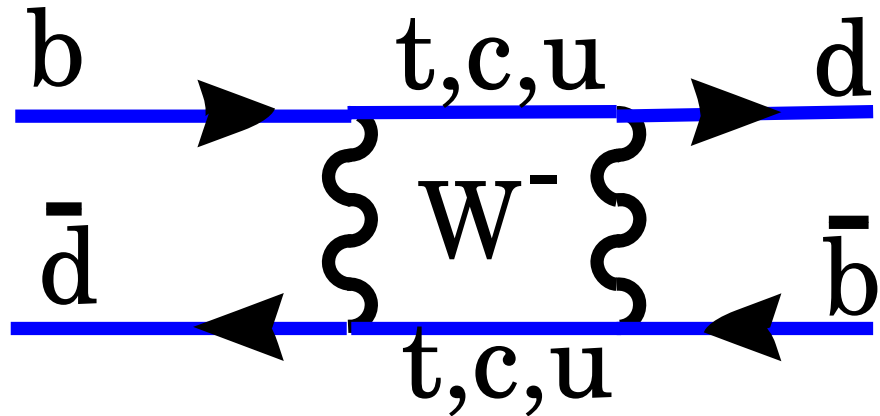
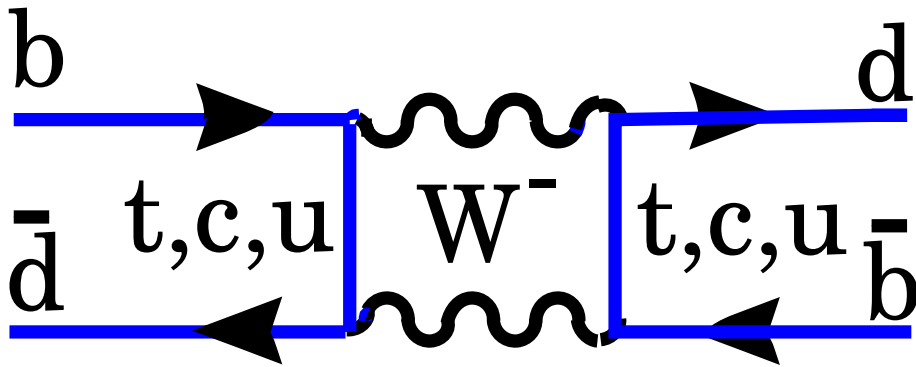


# B-mixing I

Time evolution of a decaying particle:  $B(t) = \exp[-im_B t - \Gamma_B/2t]$   
 can be written as

$$i \frac{d}{dt} \begin{pmatrix} |B(t)\rangle \\ |\bar{B}(t)\rangle \end{pmatrix} = \left( \hat{M} - \frac{i}{2} \hat{\Gamma} \right) \begin{pmatrix} |B(t)\rangle \\ |\bar{B}(t)\rangle \end{pmatrix}$$

**BUT:** In the neutral  $B$ -system transitions like  $B_{d,s} \rightarrow \bar{B}_{d,s}$  are possible due to weak interaction: **Boxdiagrams**



$\Rightarrow$  off-diagonal elements in  $\hat{M}$ ,  $\hat{\Gamma}$ :  $M_{12}$ ,  $\Gamma_{12}$  (complex)

Diagonalization of  $\hat{M}$ ,  $\hat{\Gamma}$  gives the physical eigenstates  $B_H$  and  $B_L$  with the masses  $M_H$ ,  $M_L$  and the decay rates  $\Gamma_H$ ,  $\Gamma_L$

CP-odd:  $B_H := p B + q \bar{B}$  , CP-even:  $B_L := p B - q \bar{B}$  with  $|p|^2 + |q|^2 = 1$



# B-mixing II

$|M_{12}|$ ,  $|\Gamma_{12}|$  and  $\phi = \arg(-M_{12}/\Gamma_{12})$  can be related to three observables:

■ **Mass difference:**  $\Delta M := M_H - M_L = 2|M_{12}| \left( 1 + \frac{1}{8} \frac{|\Gamma_{12}|^2}{|M_{12}|^2} \sin^2 \phi + \dots \right)$

$|M_{12}|$  : heavy internal particles: t, SUSY, ...

■ **Decay rate difference:**  $\Delta\Gamma := \Gamma_L - \Gamma_H = 2|\Gamma_{12}| \cos \phi \left( 1 - \frac{1}{8} \frac{|\Gamma_{12}|^2}{|M_{12}|^2} \sin^2 \phi + \dots \right)$

$|\Gamma_{12}|$  : light internal particles: u, c, ... (almost) no NP!!!

■ **Flavor specific/semileptonic CP asymmetries:**

$\bar{B}_q \rightarrow f$  and  $B_q \rightarrow \bar{f}$  forbidden

No direct CP violation:  $|\langle f|B_q\rangle| = |\langle \bar{f}|\bar{B}_q\rangle|$

e.g.  $B_s \rightarrow D_s^- \pi^+$  or  $B_q \rightarrow X l \nu$  (semileptonic)

$$a_{sl} \equiv a_{fs} = \frac{\Gamma(\bar{B}_q(t) \rightarrow f) - \Gamma(B_q(t) \rightarrow \bar{f})}{\Gamma(\bar{B}_q(t) \rightarrow f) + \Gamma(B_q(t) \rightarrow \bar{f})} = -2 \left( \left| \frac{q}{p} \right| - 1 \right) = \text{Im} \frac{\Gamma_{12}}{M_{12}} = \frac{\Delta\Gamma}{\Delta M} \tan \phi$$



# Theoretical framework - SM

Theoretical determination of observables

$$\frac{1}{\tau} = \sum_X \Gamma(B \rightarrow X),$$

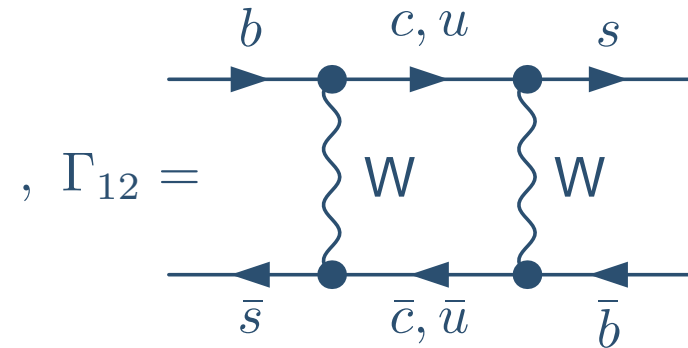
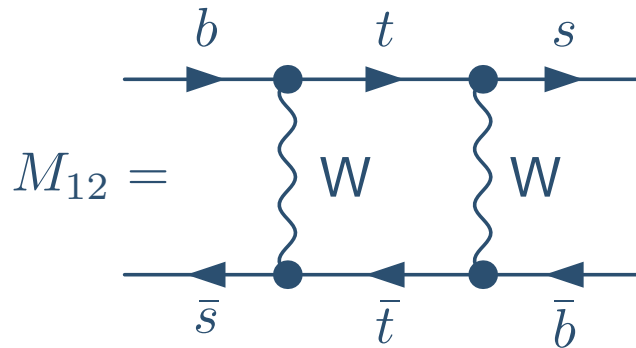
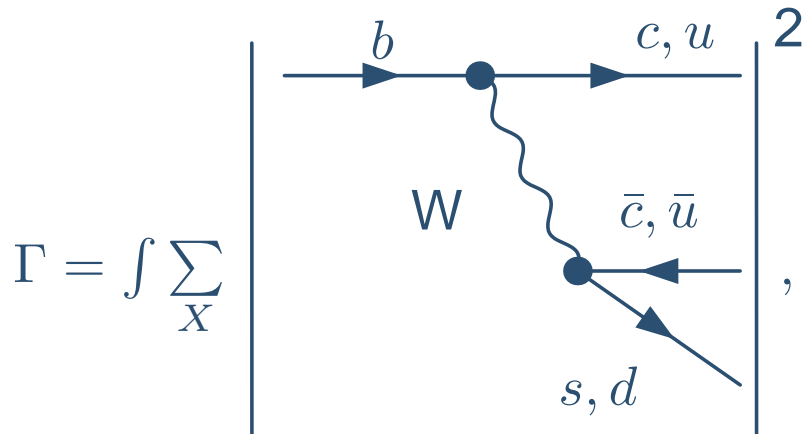
$$\Delta M = 2|M_{12}|,$$

$$\Delta\Gamma = 2|\Gamma_{12}| \cos(\phi),$$

$$a_{sl} = \Im \left( \frac{\Gamma_{12}}{M_{12}} \right),$$

$$\phi = \arg \left( -\frac{M_{12}}{\Gamma_{12}} \right).$$

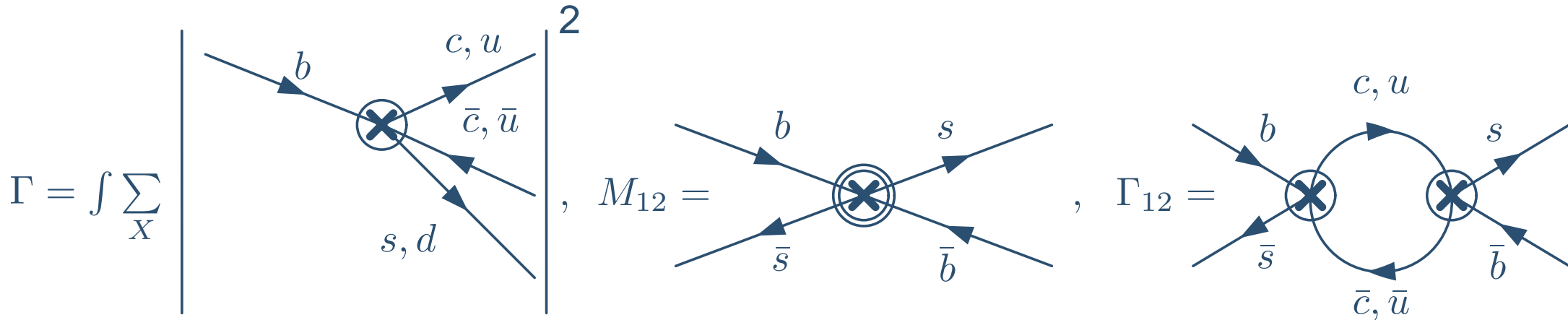
These quantities correspond to the following SM diagrams



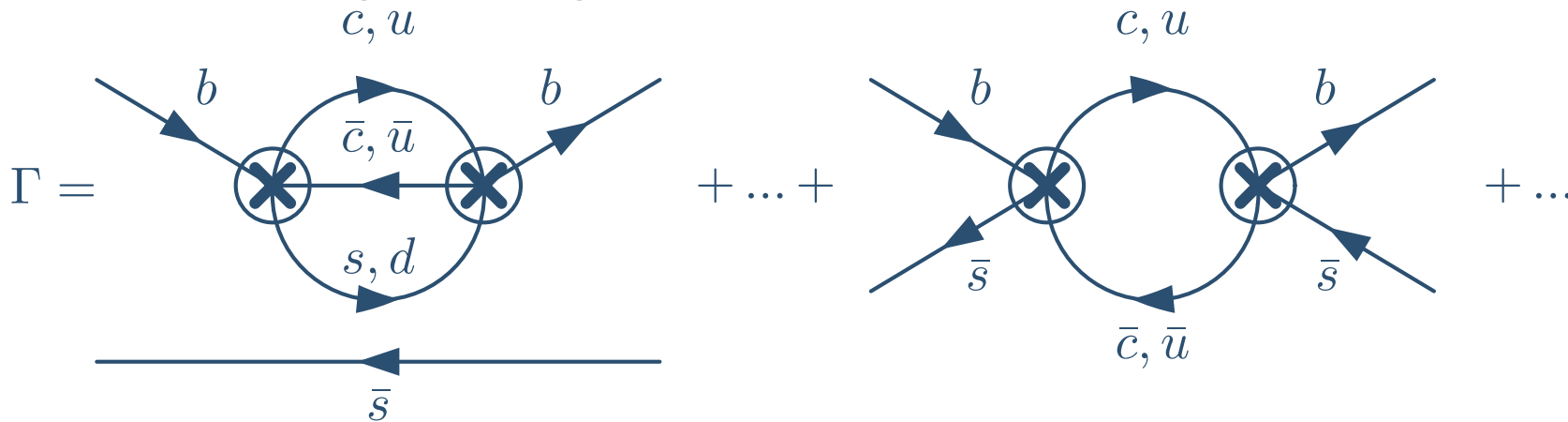


# Theoretical framework - OPE I

Use the fact:  $m_t, M_W \gg m_b$  - integrate out heavy particles



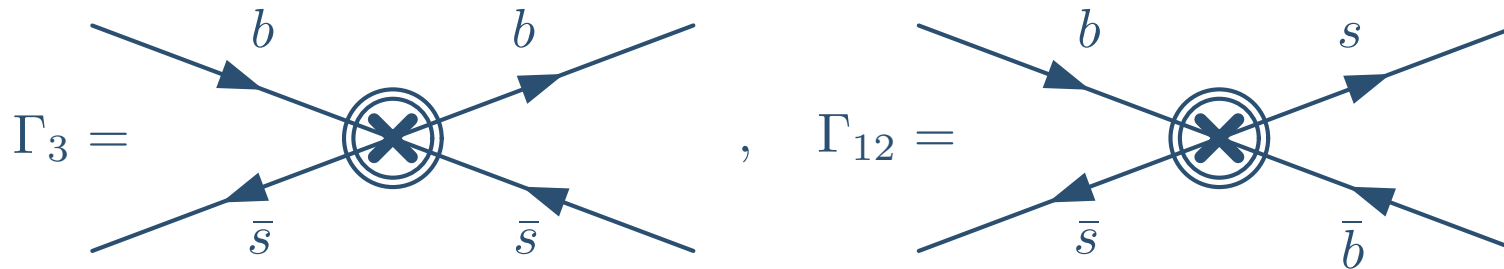
Rewrite  $\Gamma$  with the help of the optical theorem





# Theoretical framework - OPE II

Use the fact:  $m_b \gg \Lambda_{QCD}$  for  $\Gamma_0$ ,  $\Gamma_3$  and  $\Gamma_{12}$  - also local operators



- $\Gamma$ ,  $M_{12}$  and  $\Gamma_{12}$  are expressed in terms of local  $\Delta B = 0, 2$ -operators
- Determination of  $\Gamma_3$  and  $\Gamma_{12}$  almost identical
- **OPE II might be questionable**
  - $\Rightarrow$  test reliability via lifetimes (no NP effects expected)
  - $\Rightarrow$  search for NP in  $\Gamma_{12}/M_{12}$



# Heavy Quark Expansion

Systematic expansion of the decay rate in powers of  $m_b^{-1}$  yields

$$\Gamma = \Gamma_0 + \frac{\Lambda^2}{m_b^2} \Gamma_2 + \frac{\Lambda^3}{m_b^3} \Gamma_3 + \dots$$

Voloshin, Uraltsev, Khoze, Shifman

$\Gamma_0$ : Decay of a free quark  $\Rightarrow$  **all b-hadrons have the same lifetime**

$\Gamma_2$ : First corrections due to kinetic and chromomagnetic operator

$\Gamma_3$ : Weak annihilation and Pauli interference

Distinguish between different spectators  $\Rightarrow$  **Lifetime differences**  
numerically enhanced by phase space factor  $16\pi^2$





# State of the art

Meson vs Meson

$$\frac{\tau_1}{\tau_2} = 1 + \frac{\Lambda^3}{m_b^3} \left( \Gamma_3^{(0)} + \frac{\alpha_s}{4\pi} \Gamma_3^{(1)} + \dots \right) + \frac{\Lambda^4}{m_b^4} \left( \Gamma_4^{(0)} + \dots \right) + \dots$$

Baryon vs Meson

$$\frac{\tau_1}{\tau_2} = 1 + \frac{\Lambda^2}{m_b^2} \left( \Gamma_2^{(0)} + \dots \right) + \frac{\Lambda^3}{m_b^3} \left( \Gamma_3^{(0)} + \frac{\alpha_s}{4\pi} \Gamma_3^{(1)} + \dots \right) + \frac{\Lambda^4}{m_b^4} \left( \Gamma_4^{(0)} + \dots \right) + \dots$$

Neutral Mesons

$$\frac{\Delta\Gamma}{\Gamma} = \frac{\Lambda^3}{m_b^3} \left( \Gamma_3^{(0)} + \frac{\alpha_s}{4\pi} \Gamma_3^{(1)} + \dots \right) + \frac{\Lambda^4}{m_b^4} \left( \Gamma_4^{(0)} + \dots \right) + \dots$$

$$\Gamma_i^{(j)} = C_i^{(j)} \cdot \langle Q_i^{(j)} \rangle \propto f^2 \cdot B_i^{(j)} \cdot C_i^{(j)}$$

## Perturbative corrections

- $C_3^{(0)}$ : '79...'92
- $C_4^{(0)}$ : '96...'03
- $C_3^{(1)}$ : '98...'03; incomplete for  $\Lambda_b$
- $C_5^{(0)}$ : '03...'06

## non-perturbative corrections

- $\langle Q_3 \rangle$ : prel.  $n_f = 2 + 1$  for B-mixing  
only one determination for  $\tau_{B^+}/\tau_{B_d}$   
only prel. studies for  $\Lambda_b$
- $\langle Q_4 \rangle$ : mostly VIA
- $\langle Q_5 \rangle$ : only naive estimates



# Non-perturbative Parameters I: $f_{B_s}$ - the easiest

## Sum rules, quark model

- 2002: Jamin, Lange,  $244 \pm 21$  MeV
- 2004: Cvetič et al,  $216 \pm 32$  MeV
- 2006: Ebert et al, 218 MeV
- 2007: Badalion, Simonov 222 MeV
- 2007: Choi, 234 MeV

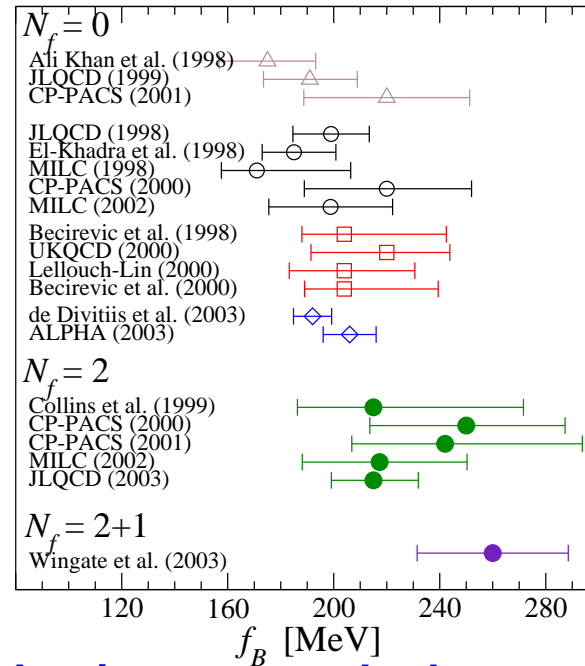
## Lattice quenched

- 2000: Becirevic et al,  $204_{-15}^{+17}$  MeV
- 2003: ALPHA,  $205 \pm 12$  MeV
- 2006: Sommer et al,  $191 \pm 6$  MeV
- 2007: Ali Khan et al,  $205 \pm 32$  MeV
- 2007: TWQCD,  $253 \pm 11$  MeV

## Lattice unquenched, $n_f = 2$

- 1999: Collins et al,  $212_{-29}^{+64}$  MeV
- 2000: CP-PACS,  $250_{-36}^{+37}$  MeV
- 2001: CP-PACS,  $242_{-35}^{+52}$  MeV
- 2002: MILC,  $217_{-22}^{+34}$  MeV
- 2003: JLQCD,  $216_{-28}^{+31}$  MeV
- 2004: UKQCD,  $256 \pm 45$  MeV

- 2005: Gadiyak, Loktik  $341 \pm 32$  MeV
- 2005: Della Morte et al  $297 \pm 14$  MeV



Hashimoto  
hep-ph/0411126

## Lattice unquenched, $n_f = 2 + 1$

- 2003: Wingate et al,  $260 \pm 29$  MeV
- 2005: HP QCD,  $259 \pm 32$  MeV
- 2007: Fermilab,  $274 \pm 32$  MeV

we use:  $f_{B_s} = 240 \pm 40$  MeV



# The decay constant problem

Compare theory predictions for  $\Delta M_s \propto f_{B_s}^2$  with experiment

$f_{B_s}$	$N_F$	$\Delta M_s$	deviation from experiment
$193 \pm 06 \text{ MeV}$	0	$12.5 \pm 1.4 \text{ ps}^{-1}$	$-3.9 \sigma$
$205 \pm 32 \text{ MeV}$	2	$14.1 \pm 4.6 \text{ ps}^{-1}$	$-0.8 \sigma$
$259 \pm 26 \text{ MeV}$	3	$22.5 \pm 5.0 \text{ ps}^{-1}$	$+0.9 \sigma$
$297 \pm 14 \text{ MeV}$	2	$30.0 \pm 3.9 \text{ ps}^{-1}$	$+3.1 \sigma$
$341 \pm 32 \text{ MeV}$	2	$39.0 \pm 8.2 \text{ ps}^{-1}$	$+2.6 \sigma$

⇒ be careful with the errors!!!



# Non perturbative Parameters II

$$\langle \bar{B}_s | (\bar{s}b)_{V-A} (\bar{s}b)_{V-A} | B_s \rangle = \frac{8}{3} M_{B_s} f_{B_s}^2 B, \dots$$

- $B, B_S$  with  $n_f = 2$  from JLQCD,01 & 03
- until 2006: only 1 published determination of  $\tilde{B}_S$ : Becirevic et al. 01
- $B, B_S$  and  $\tilde{B}_S$  with  $n_f = 2 + 1$ , staggered (HPQCD 06, Fermilab, MILC 07):  
Combined determination of  $f_{B_s} \sqrt{B_x} \Rightarrow$  smaller error

$f_{B_d}$  - extrapolation to small quark masses: e.g. HPQCD ( $n_f = 2 + 1$ ) vs. Belle

$$f_{B_d} = (216 \pm 22) \text{ MeV vs. } (229^{+47}_{-46}) \text{ MeV}$$

Clean ratio?  $\xi = \frac{f_{B_s} \sqrt{B_{B_s}}}{f_{B_d} \sqrt{B_{B_d}}} = 1.2 \dots 1.3$  (e.g. Della Morte, Lattice 07)



# $\tau_{B^+} / \tau_{B_d}$ in NLO-QCD I

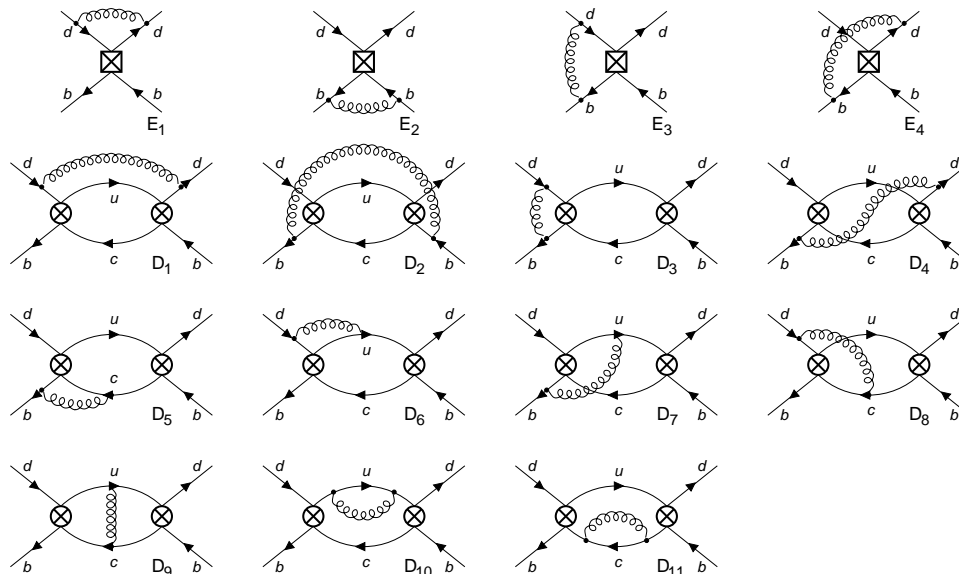
$$\frac{\tau_1}{\tau_2} = 1 + \left(\frac{\Lambda}{m_b}\right)^3 \left(\Gamma_3^{(0)} + \frac{\alpha_s}{4\pi} \Gamma_3^{(1)} + \dots\right) + \left(\frac{\Lambda}{m_b}\right)^4 \left(\Gamma_4^{(0)} + \dots\right) + \dots$$

$\Gamma_3^{(0)}$  : Shifman, Voloshin; Uraltsev; Bigi, Vainshtein; Neubert, Sachrajda

$\Gamma_4^{(0)}$  : Gabbiani, Onishchenko, Petrov; Greub, A.L., Nierste (unpublished)

$\Gamma_3^{(1)}$  : Beneke, Buchalla, Greub, A.L., Nierste; Ciuchini, Franco, Lubicz, Mescia, Tarantino

**lattice** : Di Pierro, Sachrajda, Michael; Becirevic





# $\tau_{B^+}/\tau_{B_d}$ in NLO-QCD II

$$\begin{aligned} \frac{\tau(B^+)}{\tau(B_d^0)} - 1 &= \tau(B^+) [\Gamma(B_d^0) - \Gamma(B^+)] \\ &= 0.0325 \frac{\tau(B^+)}{1.653 \text{ ps}} \left( \frac{|V_{cb}|}{0.04} \right)^2 \left( \frac{m_b}{4.8 \text{ GeV}} \right)^2 \left( \frac{f_B}{200 \text{ MeV}} \right)^2 \\ &\quad \left[ (1.0 \pm 0.2) B_1 + (0.1 \pm 0.1) B_2 - (18.4 \pm 0.9) \epsilon_1 + (4.0 \pm 0.2) \epsilon_2 \right] + \delta_{1/m} \end{aligned}$$

$(B_1, B_2, \epsilon_1, \epsilon_2) = (1.10 \pm 0.20, 0.99 \pm 0.10, -0.02 \pm 0.02, 0.03 \pm 0.01)$  '01: Becirevic

$$\left[ \frac{\tau(B^+)}{\tau(B_d^0)} \right]_{\text{LO}} = 1.047 \pm 0.049$$

$$\left[ \frac{\tau(B^+)}{\tau(B_d^0)} \right]_{\text{NLO}} = 1.063 \pm 0.027$$

NLO-QCD: '02: Beneke, Buchalla, A.L, Greub, Nierste; Ciuchini, Franco, Lubicz, Mescia, Tarantino

$1/m_b$ : '03: Gabbiani, Onishchenko, Petrov; Greub, A.L, Nierste (unpublished): tiny  $\leq 0.005$

$$\text{HFAG 08: } \left[ \frac{\tau(B^+)}{\tau(B_d^0)} \right] = 1.071 \pm 0.009$$



# The lifetime ratio $\tau_{B_s}/\tau_{B_d}$

$$\frac{\tau(B_s)}{\tau(B_d)} = 1.00 \pm 0.01$$

Neubert, Sachrajda; Beneke, Buchalla, Dunietz; Bigi, Blok, Shifman, Uraltsev, Vainshtein; U. Nierste, Y.-Y. Keum; M. Ciuchini, E. Franco, V. Lubicz, F. Mescia

Weak annihilation contributions for  $B_d$  and  $B_s$  have almost the same size.

Lifetime differences only due to small difference in phase space and by  $SU(3)_F$  violations of the hadronic parameters.

NLO penguin contributions to  $\tau_{B_s}/\tau_{B_d}$  give a comparable effect – > search for new physics

$$\text{HFAG 08: } \left[ \frac{\tau(B_s^0)}{\tau(B_d^0)} \right] = 0.961 \pm 0.018$$



# The lifetime ratio $\tau_{\Lambda_b}/\tau_{B_d}$

**Be careful!**

Theoretically in a much worse shape than  $\tau_{B^+}/\tau_{B_d}$

- NLO-QCD incomplete
- Only preliminary lattice studies for the  $\Lambda_b$  matrix elements available (di Pierro, Sachrajda)
- Certain Penguin contractions on the lattice are missing

$$\frac{\tau(\Lambda_b)}{\tau(B_d)} = 0.88 \pm 0.05$$

C. Tarantino, hep-ph/0702235; E. Franco, V. Lubicz, F. Mescia, C. Tarantino; F. Gabbiani, A. Onishchenko, A. Petrov

$$\text{HFAG 08: } \left[ \frac{\tau(\Lambda_b)}{\tau(B_d^0)} \right] = 0.904 \pm 0.032 \quad \text{CDF vs D0!!!}$$





# Lifetime of the double-heavy meson $\tau_{B_c^+}$

LO analysis gives

$$\tau(B_c) = 0.4 \dots 0.7 \text{ ps} \quad \text{vs.} \quad \tau(B_c) = 0.48 \pm 0.05 \text{ ps}$$

Beneke, Buchalla;

Colangelo et al.; Anisimov et al.; Lusignoli, Masetti; Quigg; Kiselev et al; Chang et al.

Data: HFAG 08

$$\tau(B_c) = 0.463 \pm 0.071 \text{ ps}$$



# The mass difference $\Delta M$

Calculating the Boxdiagram with an internal top-quark yields

$$M_{12,q} = \frac{G_F^2}{12\pi^2} (V_{tq}^* V_{tb})^2 M_W^2 S_o(x_t) B_{B_q} f_{B_q}^2 M_{B_q} \hat{\eta}_B$$

(Inami, Lim '81)

- Hadronic matrix element:  $\frac{8}{3} B_{B_q} f_{B_q}^2 M_{B_q} = \langle \bar{B}_q | (\bar{b}q)_{V-A} (\bar{b}q)_{V-A} | B_q \rangle$
- Perturbative QCD corrections  $\hat{\eta}_B$  (Buras, Jamin, Weisz, '90)

$$\Delta M_s = 19.3 \pm 6.7 \text{ ps}^{-1} \quad \text{better:} \quad \frac{\Delta M_s}{\Delta M_d} = \frac{M_{B_s}}{M_{B_d}} \left| \frac{V_{ts}^2}{V_{td}^2} \right| \frac{f_{B_s}^2 B_{B_s}}{f_{B_d}^2 B_{B_d}}$$

Experimental status: Heavy Flavor Averaging Group, 08

$$\Delta M_d = 0.507 \pm 0.005 \text{ ps}^{-1}$$

ALEPH, CDF, D0, DELPHI, L3, OPAL, BABAR, BELLE, ARGUS, CLEO

$$\Delta M_s = 17.77 \pm 0.10(\text{stat}) \pm 0.07(\text{syst}) \text{ ps}^{-1}$$

$$\text{CDF hep-ex/0609040, D0 5474} \quad (18.56 \pm 0.87)$$

Important bounds on the unitarity triangle and new physics



# $\Gamma_{12}$ in NLO-QCD

$$\Gamma_{12} = \left(\frac{\Lambda}{m_b}\right)^3 \left(\Gamma_3^{(0)} + \frac{\alpha_s}{4\pi}\Gamma_3^{(1)} + \dots\right) + \left(\frac{\Lambda}{m_b}\right)^4 \left(\Gamma_4^{(0)} + \dots\right) + \dots$$

$\Gamma_3^{(0)}$  : Hagelin; Buras, Slominski, Steger; Datta, Paschos, Türke, Wu;  
Voloshin, Uraltsev, Khoze, Shifman; Chau; Franco, Lusignoli, Pugliese; (1981 ...)

$\Gamma_3^{(1)}$  : Beneke, Buchalla, Greub, A.L., Nierste (1998, 2003)  
Ciuchini, Franco, Lubicz, Mescia, Tarantino (2003)

$\langle ||| \rangle$  : HPQCD, JLQCD, Becirevic et al.; Gimenez, Reyes; Jamin, Lange  
Huang, Zhang, Zhou; Blossier; Detmold, Lin... (1999 ...)

$\Gamma_4^{(0)}$  : Beneke, Buchalla, Dunietz (1996); Dighe, Hurth, Kim, Yoshikawa (2001)

$\Gamma_5^{(0)}$  : A.L., Nierste (2006), Badin, Gabbiani, Petrov (2007)

$\langle ||| \rangle$  : part of operators of dim 7 and 8 Becirevic et al (2001), Mannel et al (2007)



# New determination of $\Gamma_{12}$ : A.L., Nierste, 2006

- In the calculation of  $\Gamma_{12}$  4 operators arise:  $Q, Q_S, \tilde{Q}, \tilde{Q}_S$  [hep-ph/0612167](#), JHEP
- They are not independent:  $(\alpha_i = 1 + \mathcal{O}(\alpha_s))$

$$\tilde{Q} = Q \quad \text{and} \quad R_0 = Q_S + \alpha_1 \tilde{Q}_S + \frac{\alpha_2}{2} Q = \mathcal{O}\left(\frac{1}{m_b}\right)$$

- Old Basis:  $\{Q, Q_S\} \iff$  New Basis  $\{Q, \tilde{Q}_S\}$

Problems in the old basis: [A.L. hep-ph/0412007](#)

- :-( Almost complete cancellation in coefficient of  $Q$
- :-( Huge  $1/m_b$ -corrections
- :-( Large  $\alpha_s$ -corrections

$\Gamma_{12}^{\text{new}}$ :

- + New basis free of the above shortcomings
- + Use also  $\overline{MS}$ -scheme for  $m_b$
- + Sum  $z \ln z$  to all orders
- + Include subleading CKM structures



# $\Delta\Gamma_s$ and $\Delta\Gamma_s/\Delta M_s$

Old basis and pole scheme of  $m_b$

$$\Delta\Gamma_s = \left( \frac{f_{B_s}}{240 \text{ MeV}} \right)^2 \left[ 0.002B + 0.094B'_S - (0.033B_{\tilde{R}_2} + 0.019B_{R_0} + 0.005B_R) \right]$$

$$\frac{\Delta\Gamma_s}{\Delta M_s} = 10^{-4} \cdot \left[ 0.9 + 40.9 \frac{B'_S}{B} - \left( 14.4 \frac{B_{\tilde{R}_2}}{B} + 8.5 \frac{B_{R_0}}{B} + 2.1 \frac{B_R}{B} \right) \right]$$

New basis, sum up  $z \ln z$ , average of pole and  $\overline{\text{MS}}$ -scheme for  $m_b$

$$\Delta\Gamma_s = \left( \frac{f_{B_s}}{240 \text{ MeV}} \right)^2 \left[ 0.105B + 0.024\tilde{B}'_S - (0.030B_{\tilde{R}_2} - 0.006B_{R_0} + 0.003B_R) \right]$$

$$\frac{\Delta\Gamma_s}{\Delta M_s} = 10^{-4} \cdot \left[ 46.2 + 10.6 \frac{\tilde{B}'_S}{B} - \left( 13.2 \frac{B_{\tilde{R}_2}}{B} - 2.5 \frac{B_{R_0}}{B} + 1.2 \frac{B_R}{B} \right) \right]$$

Now a precise determination of  $\Delta\Gamma/\Delta M$  is possible!



# Why to prefer one basis?

- $\Gamma_{12}/M_{12}$ : obvious

In the new basis the dominant part has no non-perturbative contributions!!!

- $\Gamma_{12}$ : less obvious

⇒ one might think to average over the two bases  
this already reduces the uncertainties considerably

**BUT, this is a bad idea**

- ◆ Smallness of  $1/m_b$  corrections holds to all orders in QCD  
(Coefficient of  $R_0$  is color-suppressed in the new basis)

- ◆ Correlation between  $Q$ ,  $Q_S$  and  $\tilde{Q}_S$  is not taken fully into account in the old basis, large cancellations occurs

$$\tilde{B}_s - 5B_S + 4B = \mathcal{O}(\Lambda/m_b, \alpha_s)$$

⇒ **We strongly suggest to use only the new basis!!!**



# $\Delta\Gamma_s$ and $\Delta\Gamma_s/\Delta M_s$

Old basis and assume no new physics in  $B_s$ -mixing ( $\equiv f_{B_s} = 230$  MeV)

$$\frac{\Delta\Gamma_s}{\Gamma_s} = \left( \frac{\Delta\Gamma_s}{\Delta M_s} \right)^{Theory} \cdot \Delta M_s^{Exp} \cdot \tau_B^{Exp} = 0.10 \pm 0.06$$

(= Bona et al, hep-ph/0605213;)

New basis:

$$\Delta\Gamma_s = (0.096 \pm 0.039) \text{ ps}^{-1} \Rightarrow \frac{\Delta\Gamma_s}{\Gamma_s} = 0.147 \pm 0.060$$
$$\frac{\Delta\Gamma_s}{\Delta M_s} = (49.7 \pm 9.4) \cdot 10^{-4} \Rightarrow \frac{\Delta\Gamma_s}{\Gamma_s} = 0.127 \pm 0.024$$

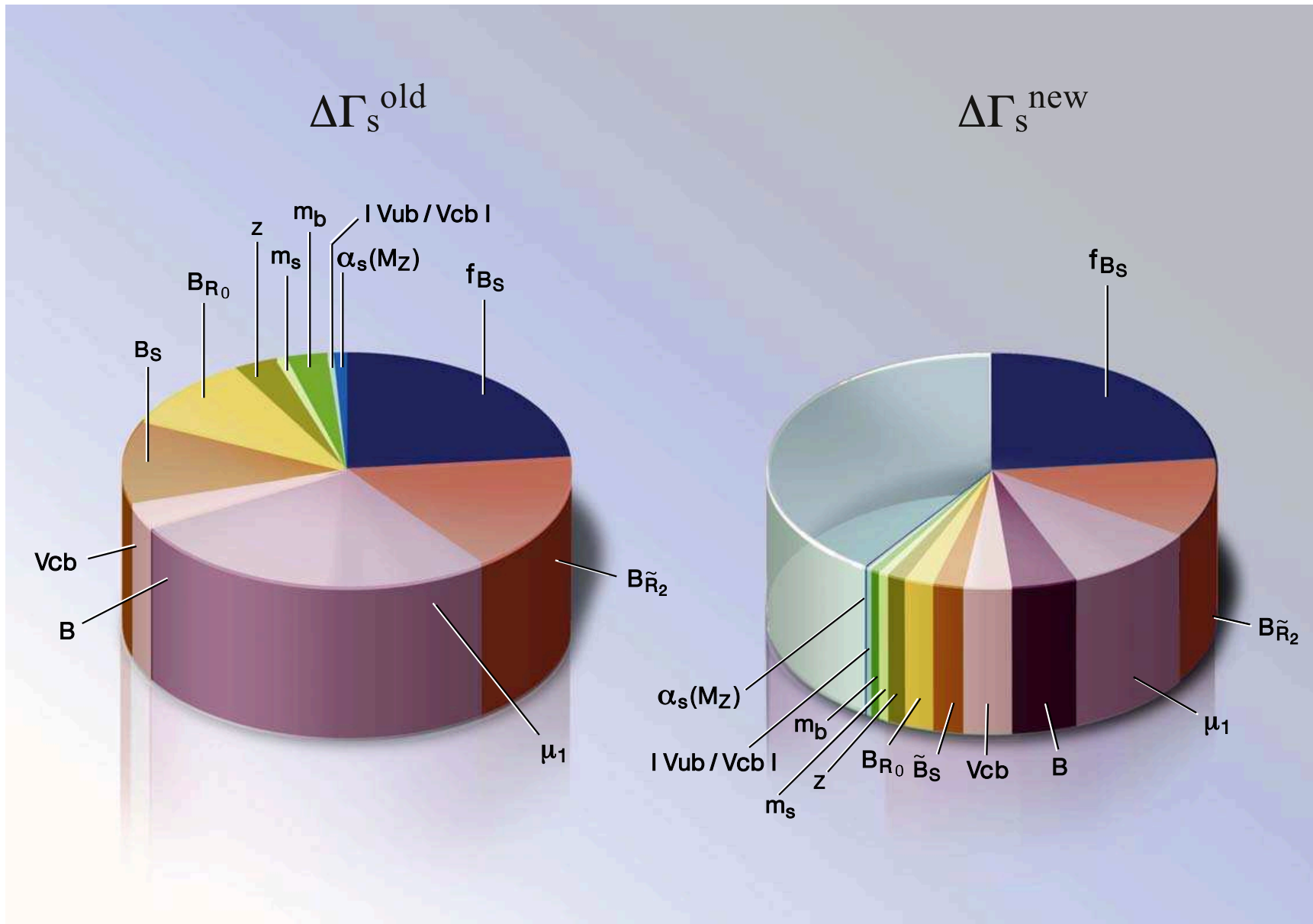
Experiment: HFAG 08 vs. D0 arXiv:0802.2255 vs. CDF arXiv:0712.2397

$$|\Delta\Gamma_s| = (0.088 \pm 0.048) \text{ ps}^{-1} \quad \text{vs.} \quad (0.19 \pm 0.07) \text{ ps}^{-1} \quad \text{vs.} \quad < (0.4 \text{ ps}^{-1})^*$$
$$\left| \frac{\Delta\Gamma_s}{\Delta M_s} \right| = (50 \pm 27) \cdot 10^{-4} \quad \text{vs.} \quad (73 \pm 51) \cdot 10^{-4} \quad \text{vs.} \quad < (225 \cdot 10^{-4})^*$$

\*: depends on  $\Phi_s$



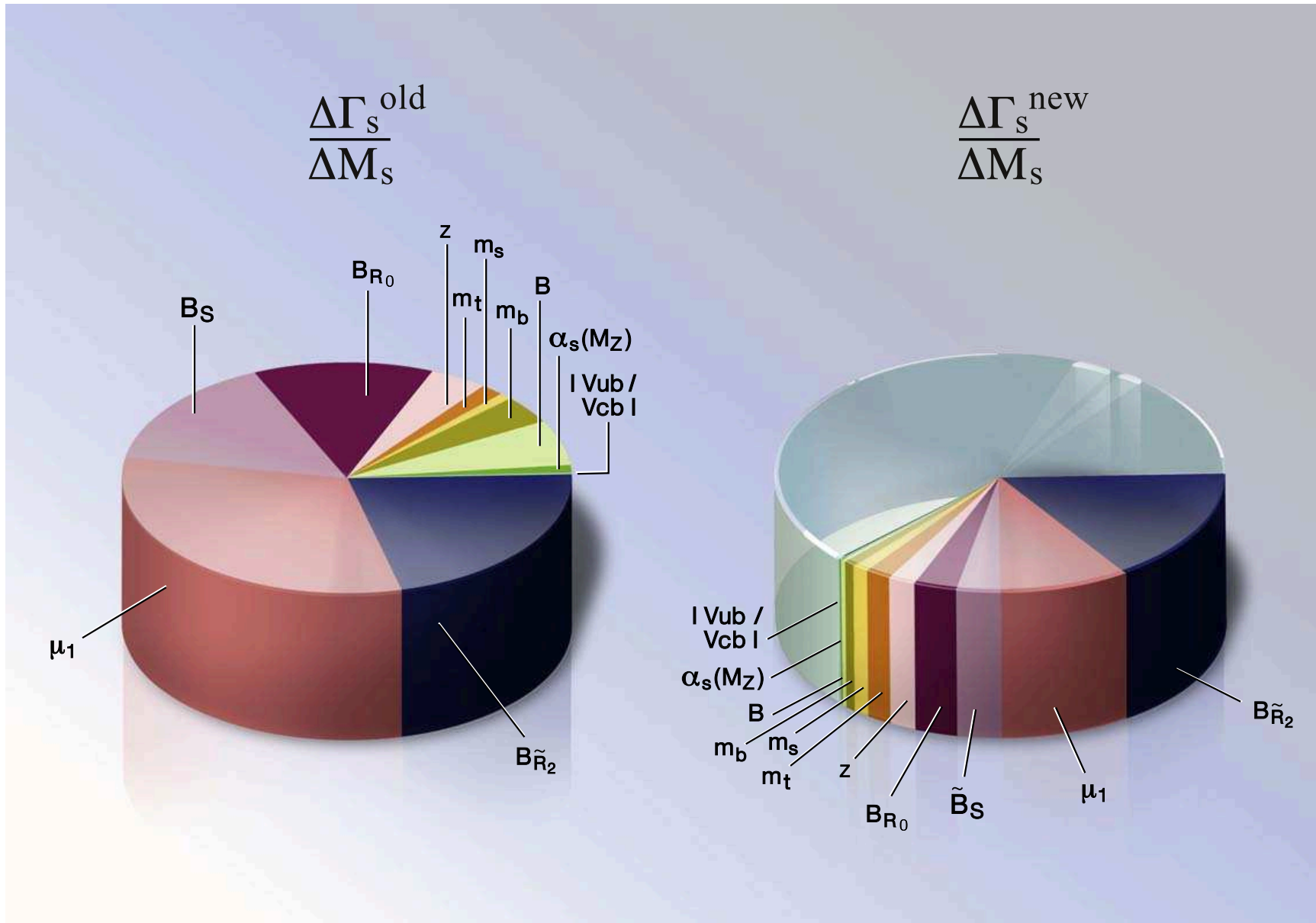
# Error budget for $\Delta\Gamma_s$







# Error budget for $\Delta\Gamma_s/\Delta M_s$





# Semileptonic CP-asymmetries $a_{fs}$ and $\Delta\Gamma_d$

SM expectations: A.L., U. Nierste, hep-ph/0612167

$$a_{fs}^s = (2.06 \pm 0.57) \cdot 10^{-5}$$

$$\phi_s = 0.24^\circ \pm 0.08^\circ$$

$$a_{fs}^d = -(4.8 \pm 1.1) \cdot 10^{-4}$$

$$\frac{\Delta\Gamma_d}{\Gamma_d} = (4.1 \pm 1.0) \cdot 10^{-3}$$

Experimental bounds

$$a_{fs}^s = -(30 \pm 1010) \cdot 10^{-5} \text{ (HFAG 08)}$$

$$\phi_s = -39.8^\circ \pm 11.2^\circ \text{ (UT-Fit, arXiv:0803.0659)}$$

$$a_{fs}^d = -(5 \pm 56) \cdot 10^{-4} \text{ (HFAG 08)}$$

$$\frac{\Delta\Gamma_d}{\Gamma_d} = (9 \pm 37) \cdot 10^{-3} \text{ (HFAG 08)}$$

typical enhancement due to NP:  $a_{fs}^s \approx 500 \cdot 10^{-5}$  close to exp. error!



# New physics in B-mixing I

There is still plenty of room for a “pinch “ of new physics in B-mixing





# New physics in mixing II

$$\Gamma_{12,s} = \Gamma_{12,s}^{\text{SM}}, \quad M_{12,s} = M_{12,s}^{\text{SM}} \cdot \Delta_s; \quad \Delta_s = 1 + \frac{S_s^{\text{new}}}{S_0(x_t)} =: |\Delta_s| e^{i\phi_s^\Delta}$$

$$\Delta_s = r_s^2 e^{2i\theta_s} = C_{B_s} e^{2i\phi_{B_s}} = 1 + h_s e^{2i\sigma_s}$$

$$\Delta M_s = 2 |M_{12,s}^{\text{SM}}| \cdot |\Delta_s|$$

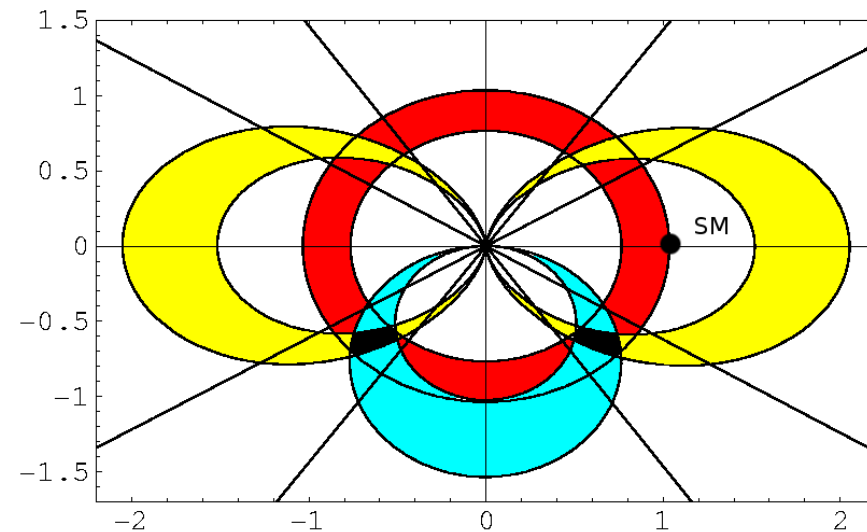
$$\Delta \Gamma_s = 2 |\Gamma_{12,s}| \cdot \cos(\phi_s^{\text{SM}} + \phi_s^\Delta)$$

$$\frac{\Delta \Gamma_s}{\Delta M_s} = \frac{|\Gamma_{12,s}|}{|M_{12,s}^{\text{SM}}|} \cdot \frac{\cos(\phi_s^{\text{SM}} + \phi_s^\Delta)}{|\Delta_s|}$$

$$a_{fs}^s = \frac{|\Gamma_{12,s}|}{|M_{12,s}^{\text{SM}}|} \cdot \frac{\sin(\phi_s^{\text{SM}} + \phi_s^\Delta)}{|\Delta_s|}$$

$$\sin(\phi_s^{\text{SM}}) \approx 1/240$$

For  $|\Delta_s| = 0.9$  and  $\phi_s^\Delta = -\pi/4$  one gets the following bounds in the **complex  $\Delta$ -plane**:





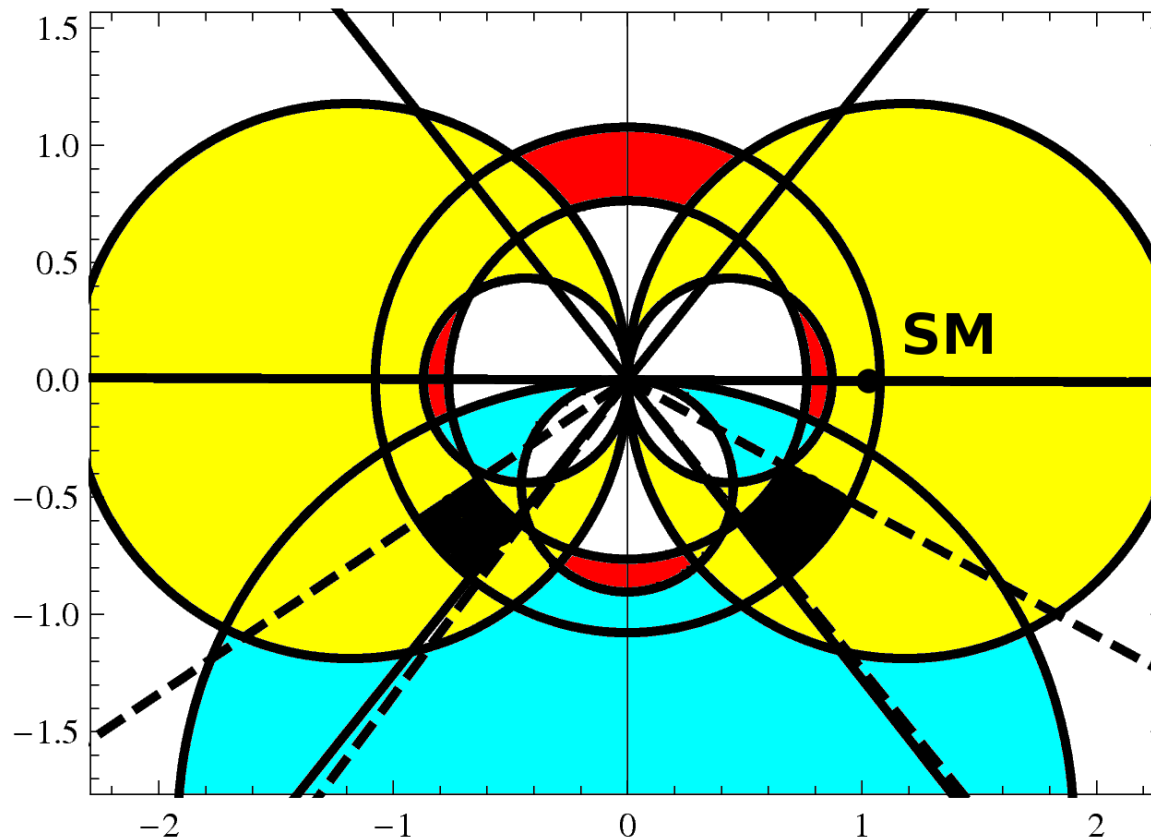
# New physics in mixing III

## Current exp. bounds:

- $\Delta M_s$
- Dimuon asymmetry
- $A_{sl}^s$  direct
- $\Delta\Gamma, \Phi_s$  ( $B_s \rightarrow J/\Psi\Phi$ )  
combined tagged number  
in progress

## Analyses

- A. L., U. Nierste, CKM-Fitter  
in preparation
- UT-Fit, arXiv:0803.0659,  
3.7  $\sigma$  deviation





# New physics in mixing IV: Examples

- SUSY:  
e.g. Gorbahn, Jäger, Nierste, Trine;  
e.g. Kifune, Kubo, A.L.  
many, many more
- Unparticle Physics:  
A.L., arXiv:0707.1535, PRD76  
  
 $|\Delta_s| \approx 1$  and  $\phi_s^\Delta \gg \phi_s^{\text{SM}}$  easily possible
- Many more ....
  - ◆ GUT
  - ◆ Extended Higgs
  - ◆ MFV
  - ◆ ...





# Conclusion - Wishlist

## Lessons from lifetimes

- **Best:**  $\tau_{B^+} / \tau_{B_d}$  perfect agreement - **but more precise values for  $B_1, B_2, \epsilon_1, \epsilon_2$  needed**
- **Best:**  $\tau_{B_s} / \tau_{B_d}$  Exp.  $2 \sigma$  below theory - **more data desirable**
- $\Lambda_b$  and  $B_c$  - **more theoretical work necessary**
- HQE seems to be in perfect shape - No signal of duality violation

## Theoretical status of mixing

- Clean prediction of  $\Gamma_{12} / M_{12}$  in new basis
- For  $M_{12}$  and  $\Gamma_{12}$  **precise values of decay constant needed**
- For higher accuracy in  $\Gamma_{12} / M_{12}$  - **non-perturbative parameters ( $B, \tilde{B}_S$  and  $B_R$ )**
- For still higher accuracy in  $\Gamma_{12} / M_{12}$  -  **$\alpha_s^2$ - and  $\alpha_s / m_b$ -corrections to  $\Gamma_{12}$**

## Experimental status of mixing

- $\Delta M_s$  and  $\Delta M_d$  perfect
- First data for  $\Delta\Gamma, a_{sl}$  and  $\Phi$  indicate a  $3.7 \sigma$ ? deviation from the SM
- **New analysis needed - more data needed**